SOME RESULTS FROM THE OBSERVATION OF ECLIPSING VARIABLES.

By RAYMOND S. DUGAN, Ph.D.

(*Read April 24, 1915.*)

At Princeton we have been using for over ten years a stellar photometer devised by Pickering and similar to the one used for so many years to such good purpose by Wendell. This photometer has many virtues and but few vices. Its construction is such that the observer has the very comfortable conviction that nearly all the sources of systematic error he can think of are being rendered innocuous by the program of observation. In accuracy it is apparently excelled by the electrical photometers alone.

A large part of our researches at Princeton has for some time been the observational and theoretical study of eclipsing variables. From the beginning we were of the opinion that the patient distribution of observations repeatedly throughout the entire period of light-variation might very possibly bring us several facts to repay us for the great labor involved.

The first star subjected to this process was *RT* Persei.[1] 14,464 measures made during the years 1905–8, combined into a mean curve, showed at once the existence of a secondary minimum, 0.13 of a magnitude in depth, and with satisfactory distinctness a slight change in brightness between eclipses. This latter change was interpreted to mean that the two stars are ellipsoidal and brighter on the sides facing each other. An asymmetry, established with considerable certainty in the curve of primary eclipse, was found to prevail throughout the entire curve. Combining this with the knowledge of one component of the eccentricity derived from the observed displacement of secondary minimum toward the preceding

[1] See Contributions from the Princeton Univ. Obs., No. 1.

primary minimum, Shapley has recently explained this asymmetry as a Periastron effect—an increased brightness of the stars when nearest each other. There is another possible explanation which I shall consider in connection with the third star.

In 1909 the series of 18,384 measures of *z* Draconis was completed.[2] Evidence of a very shallow secondary minimum, only six or seven hundredths of a magnitude in depth, displaced slightly toward the following primary minimum, was clearly found. Ellipticity of figure and exchange of radiation were again demonstrated. These two effects have been abundantly verified in other cases.

The theoretical representation of the observations of both *RT* Persei and *z* Draconis just at the beginning and end of eclipse is a little unsatisfactory—the theoretical curve starts to drop more rapidly than the observed curve. This is possibly evidence that the stars are darkened toward the limb—like the sun.

It was hoped that the observations of *RV* Ophiuchi would not only demonstrate the existence of darkening toward the limb but would determine approximately the degree of darkening. But darkening seems to be very elusive sometimes. The observed secondary minimum is barely deep enough for the uniform solution, and a darkened solution requires a still greater depth. The well-determined primary minimum is strongly asymmetrical. The inter-radiation effect is about the same as in the other two stars, while the ellipticity is much greater. This latter fact when considered with the anticipation that the ellipticity effect would in this case be too small to detect—on account of the large distance between the component stars—is somewhat disconcerting. Then too there are several well-defined hollows in the curve—a conspicuous one just after primary and another just after secondary—and a long stretch before secondary when the star is much brighter than before primary. The only satisfying method of solving the curve seemed, therefore, to be a least square solution of the whole curve—a procedure hitherto avoided. The final theoretical curve, representing our present knowledge of the causes of light variation of these stars, is the result of the solution of forty-two equations with seven

[2] See Contributions from the Princeton Univ. Obs., No. 2.

unknowns. The probable errors are of satisfactory smallness, considering the amount of asymmetry.

It seems necessary in this case to face the fact of asymmetry unflinchingly. The secondary minimum gives no evidence of an eccentric orbit and the consequent possibility of a magnified periastron effect. The most conspicuous asymmetry is a greater brightness from middle of primary eclipse through to secondary than on the other side. A sine term of the first order with an amplitude of three hundredths of a magnitude takes care of the greater part of this. The existence of this sine term would probably indicate that the advancing side of the bright star is brighter than the following. If such were the case, then the loss of light during the early stages of eclipse—when the brightest part of the disk is being covered—and the gain of light right after totality would both be more rapid than would be the case if the disk were uniformly bright, as was assumed for the least square solution. The divergence from the theoretical curve of the well observed branches of primary minimum is in this anticipated direction and it is of about the right amount. A similar asymmetry has already been remarked in the curve of *RT* Persei and is probably also, at least in part, due to this cause. This suggested explanation is of course not new, but the evidence is apparently strong that the advancing side of the brighter component of some Algol variables is brighter than the following side. After this sine term is removed from the curve of *RV* Ophiuchi, there seem to be other changes in brightness of an amount small but seemingly guaranteed by the probable error.

In the system *RT* Persei, one star is one and one third times as large and five times as bright as the other; in *z* Draconis, one star is thirteen times as bright as the other but just about equal to it in size. The eclipse is very deep and nearly total. In *RV* Ophiuchi one star is twelve times as bright as the other but smaller. The brighter star is entirely hidden behind the fainter for about an hour. The two stars are farther apart than in the other two systems but they are apparently much more elongated.

During the seven years since completing the light-curve of *RT* Persei I have observed through an occasional primary minimum both visually and photographically. Recently I have observed two secondary minima. The eclipses are now coming over forty minutes earlier than they are predicted by the elements determined from the original series of observations. This is very surprising in view of the accuracy with which the elements were determined. These elements were determined mainly from a large number of well observed minima grouped quite closely about two epochs about 700 periods apart. If the time of eclipse is fixed by the observations within a half-miniute in each of these two regions, then the period is known to one-tenth of a second. In cases where both branches of the minimum were continuously observed it seems hardly possible to change the observed time of any individual minimum by more than one or two minutes, and still represent the observations closely.

The photographic record of *RT* Persei, generously furnished me by Professor Pickering, showed that at —7,500 *P*, or 17½ years before the zero epoch, the eclipses were about 100 minutes late. The average period, then, is nearly a whole second shorter than the period determined from my original series of observations. This shorter period should have caused my observed minima to run off ten minutes from the predictions during the interval of 700 periods. This is intolerable. Beside my own observations, there are a good many observations by Wendell and several by Graff available. Of course a single estimated photographic magnitude is not nearly as accurate for determining the time of minimum as a series of photometric observations right through the eclipse.

Making now the correction to the shorter, average period, I have plotted the new residuals, and find that two periodic terms, one running its course in 12,000 eclipse-periods, or 27½ years, the other in one-third this time, or 4,000 periods, with coefficients of twelve and five minutes respectively, going through their zero values on the up grade together, fit the observations pretty well. The smaller period is of the order of magnitude of that to be expected from the revolution of the line of apsides caused by the observed prolateness of homogeneous stars. The amplitude is of the size to be expected from the smallest value of the eccentricity in accord with the observed shift of secondary minimum.

The important question, and one which is difficult to answer, is whether the time of the secondary eclipse shifts in either of these periods. The revolution of the line of apsides in the shorter period would cause the time of secondary minimum to oscillate back and forth to an extreme of ten minutes before and after the midway point between successive primaries.

The evidence is both scarce and somewhat uncertain. The entire secondary eclipse amounts to a drop of but little over a tenth of a magnitude. An isolated photographic estimate of brightness is of little value here. Even from a continuous series of photometric observations, it is difficult to fix on the time of mid-eclipse within several minutes. My own observations, weighted according to the apparent certainty with which they determine the time of mid-eclipse, indicate rather strongly the shift in the time of secondary eclipse in the shorter of the two periods. The few observations by Wendell do not furnish any very strong evidence for or against this result. In no case were his observations carried through both branches of the eclipse, and consequently they do not determine the time of the eclipse with much accuracy. What disagreement there is, is in the same direction as in the observations of primary eclipse—for some reason the Wendell times of eclipse are nearly all earlier than mine. The evidence in hand at present points to a revolution of the line of apsides of *RT* Persei. I hope to observe occasional primary and secondary minima of this star during the next few years.

As a bi-product, I have determined the photographic curve from the Harvard observations and compared it with the visual curve of primary minimum. According to the observations, the eclipses in the two regions of the spectrum are of the same duration and the same depth, but the curves follow different paths. This is too strange a result to be taken very seriously, considering the paucity of the photographic material. I have, however, one minimum which I observed through a blue color screen made for the purpose. Through this filter the minimum was observed about 0.15 magnitude deeper than without the filter. So I conclude that the observations at the bottom of the photographic curve, which are few in number, are to be disregarded and the curve extended to the greater depth given by the color-screen observations. The difference in the character of the two curves indicates that when one star is in great part covered up, the light of the system is more reddish than when they both shine undimmed. Either one star is redder than the other, or the eclipsed star is redder toward the limb than at the center.

z Draconis has been an equally interesting surprise. The average period is quite a little longer than was supposed. Some time ago it shortened up with great rapidity. The top and bottom of this sharp decline are well determined by observations from quite a variety of sources. The two sine terms combined in this case have periods of 7,200 and 2,880 eclipse-periods and nearly the same coefficients as in *RT* Persei—ten and four minutes respectively. The prolateness and eccentricity of *z* Draconis are about the same as those determined for *RT* Persei.

The secondary minimum of *z* Draconis is only 0.06 magnitude—half as deep as that of *RT* Persei; the observations of the secondary minimum are few and were all taken within a brief interval, and they furnish very little evidence. This star must also be kept under frequent observation. When observing this star with the 23-inch it requires a determined effort to see it at all when in the middle of its deep eclipse.

The greater depth of the photographic eclipse comes out very nicely in the case of *z* Draconis. As the eclipse increases, the light from the star becomes redder and redder. At deepest phase more than half the light is known to come from the fainter star. It is apparently much redder than its far brighter companion, a fact which is doubtless to be expected.

Lastly, in reducing the observations of *RV* Ophiuchi I found it necessary to predict the minima with a sine term of about 1,600 periods, and of small amplitude. The photometric history of *RV* Ophiuchi is short and incomplete compared with that of *RT* Persei and *z* Draconis, and no conclusions can safely be drawn from this result.

Princeton University,
April, 1915.